ware decreases, the economic forces increase. The resistance is steadily being reduced by new technology and by education. Therefore, we can expect a continued evolutionary introduction of advanced control in industry but no revolutionary change.

Research and development should focus on reduction of the resistance. Work should be aimed at systems that have increased reliability and maintainability, reduced cost and complexity, require less expertise to implement, are explainable to users with limited sophistication and knowledge, and can be implemented in an evolutionary fashion. There is need for education of potential users and for increased standardization whenever possible.

These are exciting times for workers in the field of industrial process control. There are great opportunities for improved operation of industrial plants by means of advanced automation. The revolutionary developments in electronics now becoming commercially established are apt to greatly accelerate the evolutionary change in process control in the next 5 to 10 years.

References and Notes

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Electronics and National Defense: A Case Study

G. P. Dinneen and F. C. Frick

As large-scale integrated circuits become available to take electronics into the homes and the daily lives of a larger public, we may see a diminution in the role that national defense will play in shaping the future growth of this technology. Up to now, however, that role has been crucial; of all the major ingredients of "the continuing revolution in electronics," only the transistor originated without the stimulus of military requirements and the support of military funding (*1*). At the same time, electronic innovation has bolstered our defenses, stimulated new concepts of military tactics and operations, and, when indulged in by others, presented major challenges to our strategic position among the nations of the world.

It is not possible to examine all these complex interactions in a short article, and we have accordingly chosen to concentrate on a particular case—the problem of aircraft surveillance and warning. We have picked this example because it is one that is most familiar to us, and also because it typifies that aspect of defense, command, and control, which is the special province of electronic technology.

Although the scientific principles that underlie modern electronics were reasonably well understood in the 1930's, it was the urgent and uniquely military requirement for early warning of possible air attack that led to the development of radar and with it the large body of associated technology that became generally available in 1947 through publication of the 28-volume Radiation Laboratory Series. The Radiation Laboratory had been established at the Massachusetts Institute of Technology in 1940 to investigate the exploitation of microwave frequencies for radar. This was considered to be a highly speculative venture at the time, but it proved to be remarkably successful in extending the usable frequency spectrum by some three orders of magnitude. Power sources were developed that could deliver several megawatts of peak power at 3000 megahertz, and kilowatts up to 24,000 megahertz. The short pulses required for good radar range resolution necessitated the design of equipment and components with megahertz bandwidths rather than the few kilohertz required for voice radio circuits. Other system needs stimulated developments that ranged from the theory and design of servomechanisms to techniques for precision engineering of large structures. Included were the pulse techniques and the cathode-ray tube and delay line storage devices that supported early electronic computer development, as well as the circuitry and components that made possible the immediate, explosive growth of television after World War II.

Only 3 years after the dissolution of the Radiation Laboratory, the problem that had stimulated the development of radar returned in a new form to force-feed the evolution of the digital computer and the digital technology that would complement the microwave technology developed during World War II. In August 1948, years earlier than expected, the Soviet Union exploded an atomic device, and, for the first time in history, the United States was forced to consider the possibility of a devastating air attack. Not only was there virtually no active air defense in being, but it was clear that early warning and raid tracking at the level of capability developed in World War II was not sufficient to meet a threat

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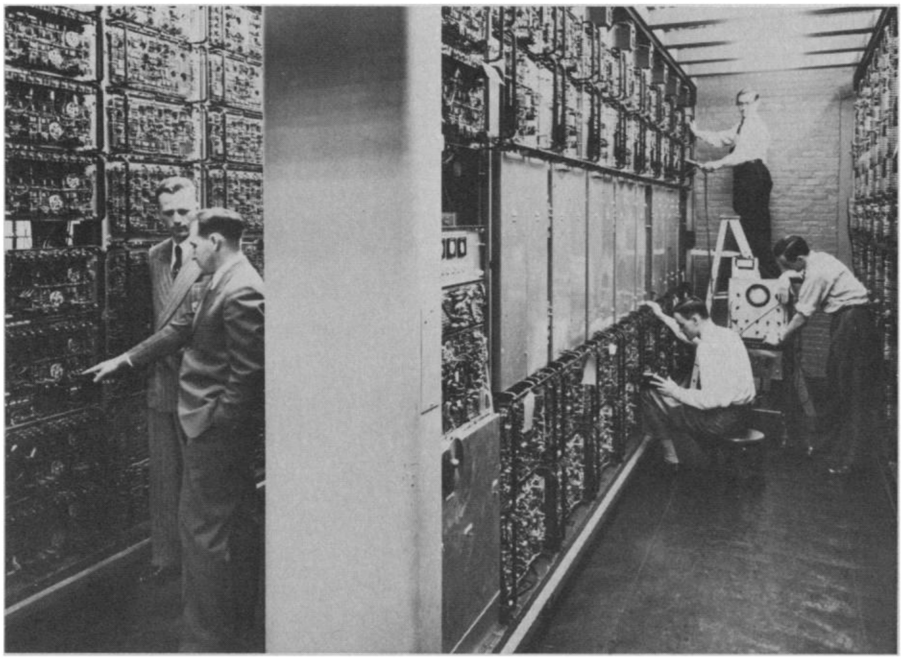

Fig. 1. WHIRLWIND 1: 14,500 vacuum tubes; 1024-word (16-bit) internal memory; operating speed, 20,000 instructions per second; computer volume, 4400 cubic feet; power required, 200 kilowatts. Shown here are the electrostatic storage and, from left to right, J. W. Forrester, N. H. Taylor, J. A. O'Brien, C. L. Corderman, and N. L. Daggett.

wherein a single aircraft could inflict more damage than could be expected from mass bombing by fleets of conventionally armed planes (2). Furthermore, if the defense was to have sufficient time to intercept high-speed jet aircraft, it would need to employ large, long-range ground radars, and such radars could be bypassed by low-flying aircraft that would remain undetected in many regions.

The solution that was eventually proposed was to use a large number of radars, which together could provide both high- and low-altitude coverage. These were to be netted through "data analysers," which were expected to coordinate all the data from the individual radars and, in addition, it was believed, could control interceptors "at no additional cost in complexity" (3).

This admittedly hazy notion of what the central computer would be like resolved itself in prototype as the MIT WHIRLWIND (Fig. 1), which had been under construction with U.S. Navy and U.S. Air Force support since 1947 and was the first computer designed with the heavy emphasis on reliability and speed that would make it suitable for real-time applications. It was clear, however, that the technology that was available in the early 1950's was not satisfactory for the air defense application. In 1951, J. W. Forrester and R. R. Everett, leaders of the WHIRLWIND project, wrote that "no existing digital computer is more than a laboratory model with respect to the present problem. . . . As now foreseen, . . . the proposed machine will be based on transistors as the active elements in the computing circuits and three-dimensional arrays of magnetic cores for high-speed internal storage . . ." (4).

As it turned out, the Air Defense Computer (AN/FSQ-7) was not transistorized. Transistors with the uniformity, reliability, and speed that would make them suitable for the highest speed computers did not become available until the announcement of the surface barrier transistor in 1954 (5). The magnetic core memory, however, did prove successful and did remove the very serious constraints on computer development that had been imposed by the unreliability and cost of other internal information storage devices, particularly the electrostatic storage tube.

A core memory operated in the Lincoln Memory Test Computer in 1953 and was later transferred to WHIRLWIND. By 1955, core memories were commercially available in the IBM 705 and, shortly thereafter, in the IBM 704, the two machines that for some time dominated the large-scale computer field. In the meantime, the requirements of the Semi-Automatic Ground Environment (SAGE) system led to the demonstration of a number of new roles for the machine that went far beyond any previous concepts of the function of an electronic "numerical calculator," and included display generation, data management, simulation, and real-time, on-line operation.

Development of the central computer was not the only critical problem in design of the air defense system. The deficiencies of early radar (6) had forced the British to net together the stations of the "Home Chain," which formed the backbone of their early warning and tracking system for the greater part of the war. This was never a very satisfactory arrangement. Detection, identification, and tracking were all performed manually and coordinated centrally through voice and teletype reports to form a picture of the air situation. Serious delays and errors appeared to be unavoidable, and, with the advent of high-speed aircraft and nuclear weapons, such performance would be intolerable. It was apparent that some means other than "voice telling" would have to be devised to transmit radar data directly to the control center. It was also apparent that microwave relay equipment then available was expensive and not reliable over long distances, and that raw radar data would, in any event, overwhelm the capacity of the central computer.

The solution proposed was to use telephone lines that existed in all populated areas of the country, and to accept the fact that the narrow bandwidth associated with these lines would necessitate extensive filtering and processing of the radar data prior to transmission. Ultimately, this proposal required the installation of massive (up to 1000 vacuum tubes), special-purpose, digital processing equipments at each radar site. In terms of future impact, perhaps the most important outcome was that it led the American Telephone and Telegraph Company to inaugurate a generally available, high-quality, digital data service (7).

In the meantime, other military requirements initiated other developments. Missile guidance systems were an early source of support for integrated circuit development; requirements for satellite-tracking radars have supported the development of surface acoustic-wave technology and charge-coupled devices, as well as modern signal processing techniques, including pulse compression and matched filtering. The need for reliable military communications has led to the exploitation of tropospheric and ionospheric scatter, to spread-spectrum and noise modulation systems, and to the development of satellite communication to small, mobile terminals. On-line computer time-sharing, computer networks, and computer graphics were all initially supported by the military. Finally, we should mention such significant second-order developments as radio and radar astronomy, microwave spectroscopy, and instrumentation for earth-resources satellites and for modern health care, all of which are heavily dependent on concepts and components derived from military electronics.

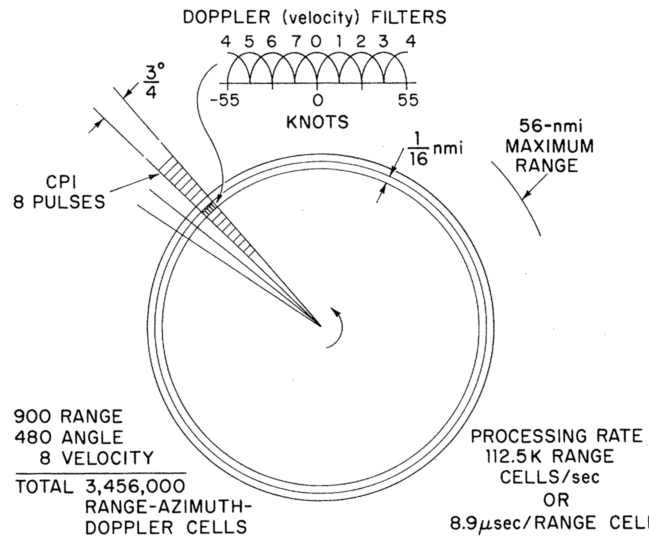

Fig. 2. Signal processing by the Moving Target Detector (MTD) for an airport surveillance radar (ASR-7).

Impact on Defense

So far, we have primarily noted the impact of defense requirements on the growth and evolution of electronics. There is, of course, a reciprocal effect. Prior to World War II (*8*)

> . . . military requirements appeared to be reasonably well understood and straightforward. Ground forces and navies were the product of long experience and gradual evolution. The increasing mobility of the tank and the long-range firepower of the aircraft were beginning to reshape the face of war, but even they were evolutionary platforms and had undergone trials in World War I and subsequent conflicts. Force planning could be, and was largely traditional and incremental although occasional and annoying innovators such as airpower and tank enthusiasts threatened to disturb the customary patterns of warfare by suggesting novel uses for newer military instruments.

Now, however, conditions have changed dramatically. Not only must we support three basic types of forces—strategic nuclear, theater nuclear, and conventional—but, as the technology of weapons, missiles, and jet aircraft which has given us almost limitless firepower and mobility becomes available to others, the classic measures of military strength must be balanced by how quickly and precisely this strength can be controlled. To quote M. R. Currie, director of Defense Research and Engineering: "Absolutely central to our strategic posture is the effectiveness of our command, control, warning, and surveillance systems. . . ." In the tactical area, "the development of integrated intelligence and target engagement systems represents the great challenge and opportunity of the next decade for DoD" (*9*).

Electronics has already, of course, given us initiative in these areas. It has supplied means for instantaneous communication with any part of the world, the capability for continuous planet-wide surveillance and a high degree of precision in weapon guidance. It is difficult, furthermore, to see how we could manage our $125-billion investment in weapon systems or assign and support 2 million uniformed personnel in more than 100 separate locations throughout the world without computer assistance and electronic information storage.

In principle, electronic information processing affords the capability that is required to coordinate our multiforce military structure and to carry out an increasingly complex defense mission. In fact, however, the multiplicity of new sensors, new information sources, and new communication capabilities tends to produce an overwhelming flow of raw data rather than the refined information that recognizes a threat, identifies targets, permits reliable tracking of a mobile opponent or, more generally, will support the degree of integration and automation that is necessary for rapid, effective control of modern military forces (*10*). It still remains to be seen whether the continuing revolution in electronics carries within it means for control and utilization of the massive flows of data which it has, in large part, spawned.

This surfeit of data appears in many areas and will not be susceptible to any single remedy. We believe, however, that there is emerging a qualitatively new capability for local information processing, derived from large-scale integrated circuitry, that carries intimations of the future resolution of many of these problems. In order to illustrate this thesis, we propose to describe in some detail recent results that have been obtained in connection with the persisting problem of aircraft surveillance and tracking. We have picked this particular development rather than comparable achievements in speech processing or radar, infrared, or visual imaging, because it is the clearest example that we know of the application of this newly available capability to the extraction of meaningful information from a vast and cluttered flow of data. We also find it interesting that the military problem of air surveillance, which has initiated so many important developments in modern electronics, is one of the first problems that may ultimately be solved through advances in that technology.

It was recognized early (*11*) that interceptions of high-speed aircraft could never be fully successful without full automation that included automatic detection and tracking, but the air defense systems of the 1950's never achieved this goal. Studies (*12*) have shown that for an automatic tracker to perform adequately in a noisy environment, the probability of target detection should be .8 or higher per scan, and the false alarm rate should be less than 10^{-5}. Despite improvements in radar resolution, moving target indication (MTI) and clutter mapping, the basic data input remained vulnerable to countermeasures, contaminated by ground returns, weather, birds, and rf interference, and the requisite performance standards could not be regularly achieved. Furthermore, to track maneuvering aircraft successfully, it is important that there be a low scan-to-scan correlation of detection dropouts. Because of these difficulties, even the most sophisticated computerized tracking algorithms have needed skillful human assistance to recover from sporadic loss of data and to track through the clutter that was inevitably present.

To achieve such low false alarm and high detection rates, it is necessary to examine the area scanned by the radar by dividing it into a large number of range-azimuth–Doppler cells (see Fig. 2). A backscatter return in such a cell is reported as a target only if the magnitude of the return is above the momentary threshold of the cell. If this threshold is set too high, the detection rate will suffer; if it is set too low, there will be a large number of false alarms triggered by various forms of noise and clutter. An optimal system will require variable (adaptive) cell thresholds that are conditioned by local context—the returns observed in the cell on prior scans and returns observed in spatially adjacent cells.

This represents a formidable data processing task which, in the particular application considered here, is accomplished through digital processing of the converted outputs of the video detector. As shown in Fig. 2, the region under surveillance is divided into 480 azimuth intervals, each 3/4° wide (one-half beam width), extending approximately 56 nautical miles in range. This range extent is divided into 900 range cells by sampling the return at a 1.3-megahertz rate, equivalent to 1/16 mile in range. The area is thus divided into 432,000 range-azimuth cells.

In each 3/4° azimuth interval, called a coherent processing interval (CPI), eight pulses are transmitted at a constant pulse repetition frequency (PRF) of approximately 1 kilohertz. On reception, eight complex digital samples are collected in each range-azimuth cell, and these are processed to produce eight Doppler (velocity) filters. This divides the area into 3,456,000 range-azimuth–Doppler cells, each of which is given its own threshold.

For targets with zero radial velocity, the detection threshold in each range-azimuth cell is a weighted average of the scan-to-scan history, which is stored in a digital map of the ground clutter. The map value is built up in a recursive manner by adding 1/8 of the output of the zero velocity filter on each scan to 7/8 of the value stored in the map. Thus, as rain moves into the area or as propagation conditions change, the map values also change. The value stored in the map is multiplied by an appropriate constant to set the threshold for the zero velocity filter.

Unlike ground clutter which has a constant spectral width centered at zero velocity, precipitation returns have a spectral shape which is set by the wind field and varies in width as well as average velocity. If the PRF of the radar is changed on successive CPI's, the very narrow Doppler spectrum of the aircraft will appear in different Doppler filters with each PRF. Except when the target's radial velocity is exactly that of the rain, aircraft returns will appear in some Doppler gate without any rain return on at least one of the two PRF's as the antenna beam scans past. It is thus possible to detect aircraft whose cross section is many decibels below the radar cross sec-

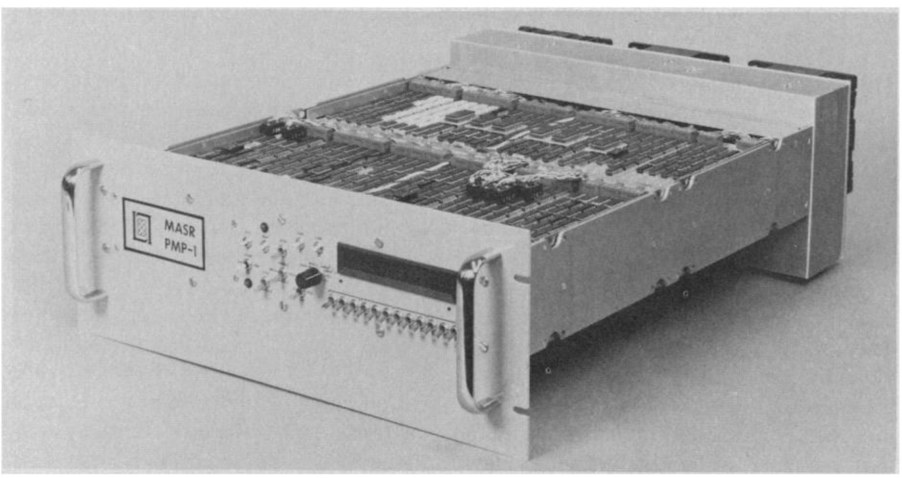

Fig. 3. Parallel Microprogrammed Processor (PMP): 3000 integrated circuits including 1024-word (24-bit) and 2048-word (60-bit) internal memories; operating speed, 25×10^6 instructions per second; computer volume, 1.8 cubic feet; power required, 160 watts.

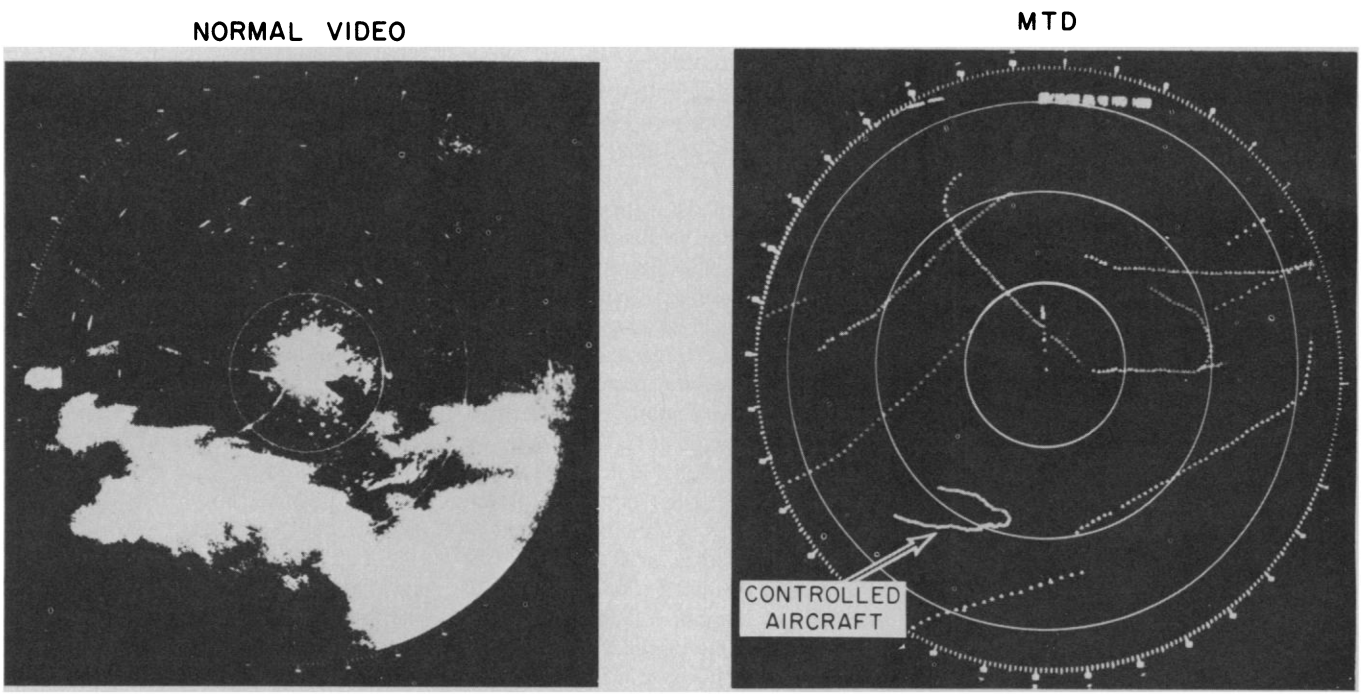

Fig. 4. Performance of the Moving Target Detector (MTD) in heavy precipitation and ground clutter. Normal video and the tracked aircraft outputs are shown. Notice the absence of false returns and the continuous tracking even of aircraft with zero radial velocity. The controlled aircraft is a single-engine Piper Cherokee.

tion of the weather return. For targets with a radial velocity, the detection threshold is set as a weighted average of returns in 16 range cells, eight on either side of the cell of interest. Blind speeds introduced by traditional MTI cancellers are also eliminated by changing the PRF every coherent processing interval.

Prototype equipment that will carry out these operations is pictured in Fig. 3. It is called the Parallel Microprogrammed Processor (PMP) and consists of a control unit and one or more identical processing modules (PM's), each containing a processing element and a data memory. Each processing element performs all the calculations on the data in its own data memory while the control unit, under microprogram control, sequences through the program in its control memory, providing instructions and data memory addresses to each PM. The operations of data collection, velocity filtering, and adaptive thresholding are performed for each range cell. The signal processor can, therefore, be a pipeline device that processes the range gates sequentially, or it can be, like the device shown in Fig. 3, an array of slower processors, all running in parallel and each processing only the data in a portion of the range window.

The results of tests performed with the Moving Target Detector (MTD), a hardwired predecessor of the equipment pictured here, have been dramatic. An example is presented in Fig. 4, and equally good performance has been observed in the presence of radio-frequency interference.

Of particular interest when considering the broader implications of such a system is the observation that the false alarm rate is so low that the entire radar output can be reliably transmitted over a telephone line, and handover or correla tion of tracks among a number of radars becomes primarily an exercise in coordinate conversion. This not only relieves the communication load, but it unburdens the central control system to operate at a different level of aggregation; for instance, to integrate radar tracking with the output of other types of sensor as might be required for full battlefield surveillance.

The technology involved—highly integrated, high-performance digital circuitry—has made it possible to carry out a massive, real-time data processing task that would not have been contemplated even a few years ago (*13*); and it has made such processing economical enough to associate this capability with each sensor, thus taking advantage of local contextual factors that, as in the example shown, are often the only means by which it is possible to extract meaningful information from the clutter in which it is generally embedded.

The low cost of digital data processing equipment also encourages duplication of circuitry for improved reliability and eventually, perhaps, completely unattended operation. The performance of the present system, for example, degrades gracefully because each PM processes only a portion of the full range window, and the failure of a PM means that the full range window continues to be processed except for that particular portion covered by the failed PM. In addition, there is a potential for self-repair in the sense that, if a PM is failing and this failure is detected by a diagnostic program running concurrently with the real-time processing program, then the processing load carried by the failed PM could be automatically switched to a standby PM. Coupled with evolutionary advances in solid-state components, nonmechanical switched-array antennas, automatic monitoring, and data-remoting equipment, such a system could operate for months at a time with no on-site maintenance or other manning.

Political and military imperatives will continue to push the technology for faster processors, larger memories, more communications, heuristic processing, worldwide conferencing, rapid and automatic translation of languages, and other electronic capabilities to ensure reliable, informed, and secure control of our military forces. Concurrently, the innovative use of the technology can have a significant effect as a "force multiplier" and in achieving economy of manpower on the battlefield.

It is expected that the shared interest of industry and the public generally will make them partners in the development of these capabilities; but if history is a guide, considerations of national defense will continue to provide a major impetus for the invention and innovation that is necessary to maintain a continuing evolution in electronics.

References and Notes

1. Even here the military presence has been significant in the continuing development of solid state electronics. It was major U.S. Air Force funding that led to the development of the silicon transistor in 1954. The need for simplified field maintenance and the stringent power and weight constraints on airborne equipment motivated Air Force support of "molecular electronics," an unfortunately named project that was nevertheless one of the key initiating events in the development of integrated circuits [P. E. Haggerty, *Proc. IEEE* **52**, 1400 (1964); M. F. Wolff, *IEEE Spectrum* **13**, 45 (1976)].
2. J. R. Killian, Jr., and A. G. Hill, *Atlantic Monthly*, November 1953.
3. Memorandum on Activities of the Air Defense System Engineering Committee, 7 April 1950, cited in *Lincoln Laboratory Quarterly Progress Report*, 1 June 1952, p. xii. The same memorandum concludes: "The type of mechanism best suited to perform this function is called a digital computer. It is similar in general idea to an IBM punched card bookkeeping machine but thousands of times faster . . . it is expected that about 100 data analysers will be required to cover 2,000,000 square miles at a price of about $500,000 per unit."
4. Memo to Project Lincoln Steering Committee, 5 October 1951.
5. J. L. Mitchell and K. H. Olsen, *Proceedings of the Eastern Joint Computer Conference* (December 1956), pp. 93–101.
6. L. N. Ridenour, Ed., *Radar System Engineering* (McGraw-Hill, New York, 1947), pp. 175 and 228.
7. The telephone company was a reluctant partner. In the early 1950's, it was not easy to see much general demand for the transmission of digital information.
8. D. H. Rumsfeld, *Report of Secretary of Defense to the Congress*, 1976.
9. M. H. Currie, *Department of Defense Program of Research, Development, Test and Evaluation, FY 1977* (February 1976).
10. "Military radioelectronics assures not only the use of missiles, anti-missiles, and other technical means of combat, but also reconnaissance, the control of troops, forces, and weapons as a whole. It is the basis of the solution of the problem of complex automation of the processes of staff activity. Without complex automation, effective command of the armed forces and consequently their successful use in a modern war will be impossible," V. D. Sokolovskiy, in *Soviet Military Strategy (1968)*, H. F. Scott, Ed. (Crane Russak, New York, 1975), p. 198.
11. Letter, Director of R & D, Deputy Chief of Staff to Commanding General of the Air Defense Command, 16 January 1948, quoted in *History of the Electronics Systems Division*, AF Support Command Historical Publication 65-30-1 (Government Printing Office, Washington, D.C., 1964).
12. The work on radar data processing reported here was carried out under the direction of C. E. Muehe, MIT Lincoln Laboratory, and we have borrowed heavily from reports given by Muehe and members of his group. It is interesting that the initial development of the MTD radar processor was supported by the FAA for "air traffic control" rather than the military for "aircraft control and warning."
13. Some substance is given to this comment by a comparison of the PMP with Illiac IV. Illiac IV was designed in the mid-1960's to be the most powerful computer that the state-of-the-art would permit. It is the largest single machine in operation, and it is capable of executing approximately 200 million instructions per second [see W. J. Bouknight, S. A. Denenberg, D. E. McIntyre, J. M. Randall, A. H. Sameh, D. L. Slotnick, *Proc. IEEE* **60**, 369 (1972), and Howard Falk, *IEEE Spectrum* **13**, 65 (1976)]. An expanded PMP, with five processing modules, would be capable of executing approximately 125 million instructions per second.

14. This article was prepared at Lincoln Laboratory, a center for research operated by MIT with the support of the Department of the Air Force under contract F19628-76-C-0002.